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RAY METHODS FOR ACOUSTIC SCATTERING, OPTICS OF BUBBLES,
DIFFRACTION CATASTROPHES, AND NONLINEAR ACOUSTICS

Philip L. Marston
Department of Physics
Washington State University
Pullman, Washington 99164-2814

Final Technical Report for Contract N00014-85-C-0141

November 1992

Prepared for: Office of Naval Research
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ABSTRACT

This report indexes research completed in several areas: (A) Ray Methods for the Scattering of Sound by Elastic Objects in Water -- Glory scattering was analyzed for solid and fluid spheres and calibration targets. Ray methods were extended to leaky Rayleigh and whispering gallery waves and then to leaky Lamb waves on shells. A related product expansion of the S function was studied. (B) Acoustical and Optical Diffraction Catastrophes -- These were observed and calculated for several situations of varying degree of complexity. (C) Light Scattering by Bubbles in Water -- Observations and physical optics approximations for backward and forward glories, critical angle scattering, optical levitation, and photoacoustic emission. (D) Nonlinear Acoustics and Radiation Pressure -- Included studies of the interaction of sound with sound in bubble layers and free surfaces, radiation pressure and torques on drops, rapid cavitation due to shock reflection, and the response of hydrodynamic shear layers to oscillations.

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I. INTRODUCTION AND ORGANIZATION OF THIS REPORT

This Final Technical Report indexes the research results of the contract N00014-85-C-0141. The proposals were titled "Propagation and Effects of Acoustical and Optical Waves" and the research involved a range of related topics in acoustics and light scattering. Section II lists the personnel involved in the research. Section III gives a bibliography of publications, reports, dissertations, and communications resulting from the sponsored research. Sections IV - VIII break the topics down into research task area and list the publications according to research topics. From the listing of the titles, the nature of the results will be evident. Section IX lists references that pertain to comments on the research made in Section IV - VIII.

This report also indexes all publications pertaining to the contract (N00014-80-C-0838) that expired at the beginning of N00014-85-C-0141. Support other than solely from N00014-85-C-0141 is indicated in Sections II and III as follows:

- ** Supported by N00014-80-C-0838 (in effect from July 1, 1980 - December 31, 1984).
- * Initial stages supported by N00014-80-C-0838 and completed under N00014-85-C-0141.
- † Supplemented by non Federal support.

II. PERSONNEL

The following persons participated in the research. Persons are listed roughly chronologically according to the time they entered the program. The area of research is indicated.

Graduate Students

1. **D. S. Langley: completed Ph.D. in 1984 on light scattering by bubbles and participated in acoustical scattering calculations.
2. **D. L. Kingsbury: completed M.S. thesis in 1981 on light scattering by bubbles and participated in acoustical scattering calculations.
3. **†S. G. Goosby: completed M.S. thesis in 1981 on acoustic levitation.

4. ****†S. Lo-Porto Arione:** awarded M.S. degree in 1991 with projected supported research.
5. ****T. J. B. Hanson:** awarded M.S. degree in 1992 with project supported acoustical scattering experiment.
6. ****R. A. Johnson:** awarded M.S. degree in 1992 and participated in light scattering research.
7. ***B. T. Unger:** awarded M.S. degree in 1982 with shock wave research and completed Ph.D. dissertation in 1986 with photoacoustics research. He also completed while in the program certification for teaching in public schools.
8. ****B. L. Brim:** awarded M.S. degree in 1983 with scattering research.
9. ***K. L. Williams:** awarded M.S. degree in 1983 with acoustical scattering research and completed Ph.D. dissertation in 1985 on acoustical scattering research.
10. **W. P. Arnott:** awarded M.S. degree in 1986 with light scattering research and completed Ph.D. dissertation in 1988 on scattering.
11. **S. C. Billette:** completed M.S. thesis in 1986 on light scattering, supported partially by N00014-86-K-0242.
12. **S. G. Kargl:** awarded M.S. degree in 1987 with scattering research and completed Ph.D. dissertation in 1990 on scattering by shells. He also carried out several nonlinear acoustics experiments.
13. **S. M. Baumer:** completed M.S. thesis in 1988 on light scattering.
14. **C. E. Dean:** completed Ph.D. dissertation in 1989 on light scattering research, supported partially by N00014-87-K-6008.
15. **C. K. Frederickson:** awarded M.S. degree in 1988 with scattering research and completed Ph.D. dissertation in 1991 on acoustical diffraction catastrophes.

16. H. J. Simpson: awarded M.S. degree in 1988 with diffraction catastrophe research. He subsequently completed a Ph.D. degree in 1992 for research supported by N00014-89-J-3088.
17. J. R. Filler: completed Ph.D. dissertation in 1989 on novel oscillation induced flow instabilities.
18. J. M. Winey: awarded M.S. degree in 1990 with project on capillary wave experiments. He subsequently has been doing a Ph.D. project under Y. M. Gupta in shock wave physics.
19. G. A Mielke: participated in nonlinear scattering experiments in 1990 prior to leaving the program.
20. J. S. Stroud: awarded M.S. degree in 1991 with project on the optical detection of transient bubble oscillations, supported partially by N00014-91-J-1374. He has subsequently been working on a Ph.D. project in acoustics with other support.
21. G. Kaduchak: awarded M.S. degree in 1992 with project on the detection of optical E₆ diffraction catastrophes. He has been working on a Ph.D. project on acoustical scattering research with other support.

Other Personnel

1. P. L. Marston: principal investigator.
2. N. H. Sun: postdoctoral researcher who contributed to scattering theory and computations in 1990 and 1991.

III. BIBLIOGRAPHY OF PUBLICATIONS, DISSERTATIONS, AND REPORTS

Research publications, dissertations, technical and internal reports, and abstracted oral presentations are listed according to category. Items available through the Defence Technical Information Center show a DTIC AD number. Items with other support are so indicated by the code noted in Section I.

Code J: Refereed Journal Publications.

- J1. P. L. Marston and D. L. Kingsbury, "Scattering by a Bubble in Water Near the Critical Angle: Interference Effects," J. Opt. Soc. Am. **71**, 192-196 (1981).**
- J2. D. L. Kingsbury and P. L. Marston, "Mie Scattering Near the Critical Angle of Bubbles in Water," J. Opt. Soc. Am. **71**, 358-361 (1981).**
- J3. P. L. Marston, S. E. LoPorto-Arione, and G. L. Pullen, "Quadrupole Projection of the Radiation Pressure on a Compressible Sphere," J. Acoust. Soc. Am. **69**, 1499-1501 (1981).**†
- J4. D. L. Kingsbury and P. L. Marston, "Scattering by Bubbles in Glass: Mie Theory and Physical Optics Approximation," Applied Optics **20**, 2348-2350 (1981).**
- J5. D. S. Langley and P. L. Marston, "Glory in the Optical Backscattering from Air Bubbles," Physical Review Letters **47**, 913-916 (1981).**
- J6. P. L. Marston and D. L. Kingsbury, "Acoustic Scattering from Fluid Spheres: Diffraction and Interference Near the Critical Scattering Angle," Journal of the Acoustical Society of America **70**, 1488-1495 (1981).**
- J7. P. L. Marston, D. S. Langley, and D. L. Kingsbury, "Light Scattering by Bubbles in Liquids: Mie Theory, Physical-Optics Approximations, and Experiments, Applied Scientific Research **38**, 373-384 (1982).**
- J8. P. L. Marston and D. S. Langley, "Glory in Backscattering: Mie and Model Predictions for Bubbles and Conditions on Refractive Index in Drops," Journal of the Optical Society of America **72**, 456-459 (1982).**
- J9. P. L. Marston and D. S. Langley, "Glory- and Rainbow-Enhanced Acoustic Backscattering from Fluid Spheres: Models for Diffracted Axial Focusing," Journal of the Acoustical Society of America **73**, 1464-1475 (1983).**
- J10. P. L. Marston, "Light Scattering by Bubbles in Liquids: Comments and Applications of Results to Circularly Polarized Incident Light," Applied Scientific Research **40**, 3-5 (1983).**

- J11. P. L. Marston, K. L. Williams, and T. J. B. Hanson, "Observation of the Acoustic Glory: High-Frequency Backscattering from an Elastic Sphere," *Journal of the Acoustical Society of America* **74**, 605-618 (1983).**
- J12. P. L. Marston, J. L. Johnson, S. P. Love, and B. L. Brim, "Critical Angle Scattering of White Light from a Cylindrical Bubble in Glass: Photographs of Colors and Computations," *Journal of the Optical Society of America* **73**, 1658-1664 + Plate X (1983).**
- J13. P. L. Marston, "Uniform Mie-theoretic Analysis of Polarized and Cross-Polarized Optical Glories," *Journal of the Optical Society of America* **73**, 1816-1818 (1983).**
- J14. D. S. Langley and P. L. Marston, "Critical-Angle Scattering of Laser Light from Bubbles in Water: Measurements, Models, and Applications to Sizing of Bubbles," *Applied Optics* **23**, 1044-1054 (1984).**
- J15. P. L. Marston, "Half-Order Derivative of Sine-Wave Burst: Applications to Two-Dimensional Radiation, Photoacoustics, and Focused Scattering from Spheres and a Torus," *Journal of the Acoustical Society of America* **76**, 291-295 (1984).**
- J16. K. L. Williams and P. L. Marston, "Mixed-Mode Acoustical Glory Scattering from a Large Elastic Sphere: Model and Experimental Verification," *Journal of the Acoustical Society of America* **76**, 1555-1563 (1984).**
- J17. P. L. Marston and J. H. Crichton, "Radiation Torque on a Sphere Caused by a Circularly Polarized Electromagnetic Wave," *Physical Review A* **30**, 2508-2516 (1984) reprinted in Selected Papers on Light Scattering, edited by Milton Kerker, *Proc. SPIE* **951**, 414-422 (1988).**
- J18. P. L. Marston and E. H. Trinh, "Hyperbolic umbilic diffraction catastrophe and rainbow scattering from spheroidal drops," *Nature (London)* **312**, 529-531 (1984).
[** and supported partially by NASA.]
- J19. P. L. Marston and S. G. Goosby, "Ultrasonically stimulated low-frequency oscillation and breakup of immiscible liquid drops: Photographs," *Physics of Fluids* **28**, 1233-1242 (1985).**†

- J20. K. L. Williams and P. L. Marston, "Axially Focused (Glory) Scattering due to Surface Waves Generated on Spheres: Model and Experimental Confirmation using Tungsten Carbide Spheres," *Journal of the Acoustical Society of America* **78**, 722-728 (1985).*
- J21. K. L. Williams and P. L. Marston, "Backscattering from an elastic sphere: Sommerfeld-Watson transformation and experimental confirmation," *Journal of the Acoustical Society of America* **78**, 1093-1102 (1985); **79**, 2091 (1986).*
- J22. P. L. Marston "Cusp diffraction catastrophe from spheroids: generalized rainbows and inverse scattering," *Optics Letters* **10**, 588-590 (1985).
- J23. K. L. Williams and P. L. Marston, "Synthesis of backscattering from an elastic sphere using the Sommerfeld-Watson transformation and giving a Fabry-Perot analysis of resonances," *Journal of the Acoustical Society of America* **79**, 1702-1708 (1986).*
- J24. P. L. Marston, "Transverse cusp diffraction catastrophes: Some pertinent wavefronts and a Pearcey approximation to the wavefield," *Journal of the Acoustical Society of America* **81**, 226-232 (1987).
- J25. P. L. Marston, "GTD for backscattering from elastic spheres and cylinders in water, and the coupling of surface elastic waves with the acoustic field," *Journal of the Acoustical Society of America* **83**, 25-37 (1988).
- J26. B. T. Unger and P. L. Marston, "Optical levitation of bubbles in water by the radiation pressure of a laser beam: an acoustically quiet levitator," *Journal of the Acoustical Society of America* **83**, 970-975 (1988).
- J27. W. P. Arnott and P. L. Marston, "Optical glory of small freely-rising gas bubbles in water: Observed and computed cross-polarized backscattering patterns," *Journal of the Optical Society of America* **A5**, 496-506 (1988).
- J28. S. G. Kargl and P. L. Marston, "Observations and modeling of the backscattering of short tone bursts from a spherical shell: Lamb wave echoes, glory, and axial reverberations," *Journal of the Acoustical Society of America* **85**, 1014-1028 (1989).

- J29. W. P. Arnott and P. L. Marston, "Unfolding axial caustics of glory scattering with harmonic angular perturbations of toroidal wavefronts," *Journal of the Acoustical Society of America* **85**, 1427-40 (1989).
- J30. P. L. Marston, "Phase velocity of Lamb waves on a spherical shell: Approximate dependence on curvature from kinematics," *Journal of the Acoustical Society of America* **85**, 2663-65 (1989).
- J31. S. G. Kargl and P. L. Marston, "Ray synthesis of Lamb wave contributions to the total scattering cross section for an elastic spherical shell," *Journal of the Acoustical Society of America* **80**, 1103-1113 (1990).
- J32. S. G. Kargl and P. L. Marston, "Longitudinal resonances of the form function for backscattering from a spherical shell: Fluid shell case," *Journal of the Acoustical Society of America* **88**, 1114-1112 (1990).
- J33. S. G. Kargl and P. L. Marston, "Ray synthesis of the form function for backscattering from an elastic spherical shell: Leaky Lamb waves and longitudinal resonances," *Journal of the Acoustical Society of America* **89**, 2545-2558 (1991).
- J34. C. E. Dean and P. L. Marston, "Opening rate of the transverse cusp diffraction catastrophe in light scattered from oblate spheroidal drops," *Applied Optics* **30**, 3443-3451 (1991).
- J35. W. P. Arnott and P. L. Marston, "Unfolded optical glory of spheroids: Backscattering of laser light from freely rising spheroidal air bubbles in water," *Applied Optics* **30**, 3429-3442 (1991).
- J36. D. S. Langley and P. L. Marston, "Forward glory scattering from bubbles," *Applied Optics* **30**, 3452-3458 (1991).**
- J37. D. S. Langley and M. J. Morrell, "Rainbow-enhanced forward and backward glory scattering," *Applied Optics* **30**, 3459-3467 (1991).**

- J38. H. J. Simpson and P. L. Marston, "Scattering of white light from levitated oblate water drops near rainbows and other diffraction catastrophes," *Applied Optics* **30**, 3468-3473 + 3547 [Color Plates 13-16] (1991).
- J39. P. L. Marston, "Colors observed when sunlight is scattered by bubble clouds in sea water," *Applied Optics* **30**, 3479-3484 + 3549 [Color Plate 20] (1991).
- J40. J. R. Filler, P. L. Marston, and W. C. Mih, "Response of the shear layers separating from a circular cylinder to small-amplitude rotational oscillations," *Journal of Fluid Mechanics* **231**, 481-499 (1991). (Partially supported N00014-89-J-3088.)
- J41. C. E. Dean and P. L. Marston, "Critical angle light scattering from bubbles: an asymptotic series approximation," *Applied Optics* **30**, 4764-4776 (1991). (Partially supported by N00014-87-K-6008).
- J42. C. K. Frederickson and P. L. Marston, "Transverse cusp diffraction catastrophes proceeded by the reflection of ultrasonic tone bursts from a curved surface in water: Observations," *J. Acoust. Soc. Am.* **92**, 2869-2877 (1992).

Code B: Chapters in Books.

- B1. P. L. Marston and D. S. Langley, "Bubbles in Liquid ^4He and ^3He : Mie and Physical-Optics Models of Light Scattering, and Quantum Tunneling and Spinodal Models of Nucleation," in Near Zero: New Frontiers in Physics, edited by J. D. Fairbank, B. S. Deaver, C. W. F. Everitt, and P. F. Michelson (Freeman, San Francisco, 1988) pp. 127-140.**
- B2. P. L. Marston, S. G. Kargl, and N. H. Sun, "Elastic resonance amplitudes described by generalized GTD and by product expansions of the S-matrix," in Acoustic Resonance Scattering edited by H. Uberall (Gordon and Breach, New York, 1992) pp. 305-333. (Partially supported by N00014-89-J-3088.)
- B3. P. L. Marston, "Geometrical and Catastrophe Optics Methods in Scattering," in High Frequency and Pulse Scattering, in *Physical Acoustics*, Vol. XXI, edited by R. N. Thurston and A. D. Pierce (Academic Press, Boston, 1992) pp. 1-234. (Partially supported by N00014-89-J-3088.) See Section VIII for table of contents.

Code T: Theses or Dissertations.

- T1. D. L. Kingsbury, "Light Scattering Near the Critical Angle of Air Bubbles in Water and Glass," M.S. Thesis, 1980.**
- T2. S. G. Goosby, "Photographs of Breakup Induced by Modulated Acoustic Radiation Pressure," M.S. Thesis, 1981.**†
- T3. D. S. Langley, "Light Scattering from bubbles in Liquids," Ph.D. dissertation, 1984. DTIC AD-A158736.**
- T4. K. L. Williams, "Acoustical Scattering from an Elastic Sphere in Water: Surface Wave Glory, Resonances, and the Sommerfeld-Watson Transformation for Amplitudes," Ph.D. dissertation, 1985. DTIC AD-A158884.*
- T5. S. C. Billette, "Computational Analysis of the Effects of Surface Films on the Optical Scattering Properties of Bubbles in Water," M.S. Thesis, 1986. DTIC AD-A173999. [Supported partially by N00014-86-K-0242.]
- T6. B. T. Unger, "Optically Stimulated Sound from Gas Bubbles in Water," Ph.D. dissertation, 1986.
- T7. S. M. Bäumer, "Observation of Brewster Angle Light Scattering from Air Bubbles Rising in Water," M.S. Thesis, 1988. DTIC AD-A119582.
- T8. W. P. Arnott, "Generalized Glory Scattering from Spherical and Spheroidal Bubbles in Water: Unfolding Axial Caustics with Harmonic Angular Perturbations of Toroidal Wavefronts," Ph.D. dissertation, 1988.
- T9. C. E. Dean, "Analysis of scattered light: I. Asymptotic series for critical angle scattering from bubbles; II. The opening rate of the transverse cusp from oblate drops," Ph.D. dissertation, 1989.
- T10. J. R. Filler, "Response of the shear layer separating from a circular cylinder to small amplitude rotational oscillation," Ph.D. dissertation, 1989.

- T11. S. G. Kargl, "Quantitative Ray Methods for Scattering of Sound by Spherical Shells, Ph.D. dissertation, 1990. DTIC AD-A240255.
- T12. C. F. Frederickson, "Wavefields Near Transverse Cusp Caustics Produced by Reflecting Ultrasonic Transients and Tone Bursts from Curved Surfaces," Ph.D. dissertation, 1991. DTIC AD-A240641
- T13. H. J. Simpson, "Interaction of Sound with Sound by Novel Mechanisms: Ultrasonic Four-Wave Mixing Mediated by a Suspension and Ultrasonic Three-Wave Mixing at a Free Surface," Ph.D. dissertation 1992. DTIC AD-A254657 (Mostly supported by N00014-89-J-3088).

Code S: Annual Summary Reports.

- S1. P. L. Marston, D. S. Langley, and D. L. Kingsbury, Technical Report No. 1. Light Scattering by Bubbles in Liquids or in Glass, issued September 1981 for O.N.R. Contract N00014-80-C-0838 (Defense Technical Information Center, AD-A104241) 90 pages.
- S2. P. L. Marston and D. S. Langley, Technical Report No. 2. Glory and Rainbow Enhanced Backscattering from Fluid Spheres: Modes for Diffracted Axial Focusing, issued September 1982 for Contract N00014-80-C-0838 (Defence Technical Information Center, AD-A119369) 51 pages.
- S3. P. L. Marston, Focused Acoustical and Optical Backscattering from Spheres Properties of Optoacoustics Sources, Report N00014-80-C-0834-TR3 issued September 1983 (Defense Technical Information Center, AD-A133744) 53 pages.
- S4. P. L. Marston, Research on Acoustical and Optical Scattering. Optics of Bubbles. Diffraction Catastrophes. Laser Generation of Sound. and Shock Induced Cavitation, Report No. N00014-80-C-0838-AR4, issued September 1984 (Defense Technical Information Center, AD-A146703) 81 pages.
- S5. P. L. Marston, Research on Acoustical Scattering. Optics of Bubbles. Diffraction Catastrophes. and Laser Generation of Sound by Bubbles, Report No. N00014-85-

C-0141-AR5, issued September 1985 (Defense Technical Information Center, AD-A161333) 72 pages.

- S6. P. L. Marston, Research on Acoustical Scattering, Diffraction Catastrophes, Optics of Bubbles, Photoacoustics, and Acoustical Phase Conjugation, Report No. N00014-85-C-0141-AR6, issued September 1986 (Defense Technical Information Center, AD-A174401) 48 pages.
- S7. P. L. Marston, Research on Acoustical Scattering, Diffraction Catastrophes, Optics of Bubbles, Photoacoustics, and Acoustical Phase Conjugation, Report No. N00014-85-C-0141-AR7, issued September 1987 (Defense Technical Information Center, AD-A185785) 84 pages.
- S8. P. L. Marston, Research on Acoustical Scattering, Diffraction Catastrophes, Optics of Bubbles, and Acoustical Phase Conjugation, Report No. N00014-85-C-0141-AR8, issued October 1988 (Defense Technical Information Center, AD-A201451) 52 pages.
- S9. P. L. Marston, Research on Acoustical Scattering, Diffraction Catastrophes, Optics of Bubbles, Acoustical Phase Conjugation, and Wake of an Oscillating Circular Cylinder, Report No. N00014-85-C-0141-AR9, issued October 1989 (Defense Technical Information Center, AD-A214168) 56 pages.

Code P: Papers in Conference Proceedings.

- P1. P. L. Marston and G. L. Pullen, "Cavitation in Water Induced by the Reflection of Shock Waves," in Shockwaves in Condensed Matter-1981, edited by W. J. Nellis, L. Seaman, and R. A. Graham (American Institute of Physics, Proceedings No. 78, New York, 1982), pp. 515-519.**†
- P2. P. L. Marston, S. G. Goosby, D. S. Langley, and S. E. LoPorto-Arione, "Resonances, Radiation Pressure, and Optical Scattering Phenomena of Drops and Bubbles," in Proceedings of the Second International Colloquium on Drops and Bubbles, edited by D. H. LeCroissette (Jet Propulsion Laboratory, Publication 82-7, Pasadena, 1982), pp. 166-174.**†

- P3. P. L. Marston, J. L. Johnson, S. P. Love, and B. L. Brim, "Scattering of White Light from a Cylindrical Bubble: Observations of Colors Near the Critical Scattering Angle," in Digest of the Topical Meeting on Meteorological Optics (Optical Society of America, Washington, D.C., 1983), pp. ThA3.1-ThA3.4.**
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- P7. P. L. Marston and J. H. Crichton, "Radiation torque on a sphere illuminated with circularly polarized light and the angular momentum of scattered radiation," in Proceedings of the Chemical Research and Development Center's 1984 Scientific Conference on Obscuration and Aerosol Research, edited by R. H. Kohl and D. Stroud (U.S. Army, Aberdeen Proving Ground, MD, 1985) pp. 233-238.**
- P8. P. L. Marston and B. T. Unger, "Rapid Cavitation Induced by the Reflection of Shock Waves" in Shock Waves in Condensed Matter, Y. M. Gupta, editor (Plenum Press, NY, 1986) pp. 401-405.*†
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- P10. P. L. Marston, "Directional caustics in acoustics and in light scattered from bubbles," in Proceedings of the 12th International Congress on Acoustics (Beauregard Press, Toronto Canada, 1986), pp. I1-1.1/1.2.

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- P20. P. L. Marston, W. P. Arnott, S. M. Bäumer, C. E. Dean, and B. T. Unger, "Optics of Bubbles in Water: Scattering Properties, Coatings, and Laser Radiation Pressure," in Drops and Bubbles. Third International Colloquium edited by T. G. Wang (AIP Conference Proceedings 197, New York, 1989) pp. 461-480.
- P21. P. L. Marston, C. E. Dean, and H. J. Simpson, "Light Scattering from Spheroidal Drops: Exploring Optical Catastrophes and Generalized Rainbows," in Drops and Bubbles. Third International Colloquium edited by T. G. Wang (AIP Conference Proceedings 197, New York, 1989) pp. 275-285.
- P22. P. L. Marston, "Light scattering from bubbles in water," in Oceans' 89 (IEEE Publication No. 89CH2780-5, New York, 1989) pp. 1186-1193.
- P23. P. L. Marston and S. G. Kargl, "Elastic surface wave contributions to backscattering from smooth elastic objects described by a generalization of GTD," in Oceans' 89 (IEEE Publication No. 89CH2780-5, New York, 1989) pp. 1194-1198.
- P24. P. L. Marston, S. G. Kargl, and K. L. Williams, "Rayleigh, Lamb, and Whispering Gallery Wave Contributions to Backscattering from Smooth Elastic Objects in Water Described by a Generalization of GTD," in Elastic Waves and Ultrasonic Nondestructive Evaluation (IUTAM Symposium), edited by S. K. Datta, J. D. Achenbach, and Y. S. Rajapakse (Elsevier Science Publishers, Amsterdam, 1990) pp. 211-216.
- P25. C. K. Frederickson and P. L. Marston, "Transverse cusp diffraction catastrophes produced by reflecting ultrasonic tone bursts from curved surfaces," in Elastic Waves and Ultrasonic Nondestructive Evaluation (IUTAM Symposium), edited by S. K. Datta, J. D. Achenbach, and Y. S. Rajapakse (Elsevier Science Publishers, Amsterdam, 1990) pp. 411-413.
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- P27. C. E. Dean and P. L. Marston, "The opening rate of the transverse cusp diffraction catastrophe from oblate spherical water drops," Light and color in the open air, OSA Topical Meeting (Washington, D.C., 1990) Technical Digest Series, Vol. 12 pp. 8-11.
- P28. H. J. Simpson and P. L. Marston, "Scattering white light from oblate water drops near rainbows and other diffraction catastrophes," Light and color in the open air, OSA Topical Meeting (Washington, D.C., 1990) Technical Digest Series, pp.20-23.
- P29. P. L. Marston, "Colors observed when sunlight is scattered from bubble clouds in sea water," Light and color in the open air, OSA Topical Meeting (Washington, D.C., 1990) Technical Digest Series, pp. 51-54.
- P30. P. L. Marston and C. K. Frederickson, "Wavefields of Linear Cusp Caustics Germane to Nonlinear Foci," in Frontiers of Nonlinear Acoustics: 12th ISNA, edited by M. F. Hamilton and D. T. Blackstock (Elsevier, London, 1990), pp. 203-208.
- P31. P. L. Marston and S. G. Kargl, "Wavefront Reversal and Difference Frequency Generation Via Three-Wave Mixing in a Bubble Layer," in Frontiers of Nonlinear Acoustics: 12th ISNA, edited by M. F. Hamilton and D. T. Blackstock (Elsevier, London, 1990), pp. 514-519.
- P32. *Invited Paper*: P. L. Marston, T. J. Asaki, J. S. Stroud, and E. H. Trinh, "Oscillations of bubbles driven by modulated ultrasonic radiation pressure their optical detection, and the optical detection of transient bubble oscillations associated with rain noise," in *Proceedings of the 14th International Congress on Acoustics*, edited by Li Peizi (Beijing, 1992), pp. C-2-5.1, 2. (Partially supported by N00014-91-J-1374 and by NASA.)

Code I: Internal Reports. These include various reports on file that were not widely distributed. Copies will be available for a limited time from the principal investigator. Some of these have been superseded by other manuscripts that were submitted for publication.

- I1. S. Arione, "Acoustic Radiation Pressure on Drops," M.S. project report 1981.

- I2. B. Unger, "Shock Induced Cavitation," M.S. project report 1982.
- I3. T. J. B. Hanson, "An Acoustical Backscattering Experiment," M.S. project report 1982.
- I4. K. L. Williams, "Mixed Mode Acoustical Glory: Model and Experimental Verification," M.S. project report 1983.
- I5. B. L. Brim, "Brewster Angle Phenomena at Curved Surfaces," M.S. project report 1983.
- I6. W. P. Arnott, "Backscattering from Oblate Bubbles in Water and the Unfolded Glory," M.S. project report 1986.
- I7. S. G. Kargl, "Focused Backscattering of Lamb Waves from Elastic Spherical Shells in Water," M.S. project report 1987.
- I8. C. F. Frederickson, "Observation of Acoustical and Optical Transverse Cusp Catastrophes Produced by Reflection from a Curved Metal in Water," M.S. project report 1988.
- I9. H. J. Simpson, "The Lips Event for Light Backscattered from Levitated Water Drops," M.S. project report 1988.
- I10. J. M. Winey, Experiments on Wave Phenomena in a Ripple Tank," M.S. project report 1990.
- I11. J. S. Stroud, "Optical Detection of Regularly Entrained Bubbles," M.S. project report 1991.
- I12. G. Kaduchak, "Observation of the E_6 Diffraction Catastrophe by Optical Scattering from Levitated Drops in the Rainbow Region," M.S. project report 1992.

Code M: Oral Presentations at Professional Meetings. Presentations at meetings having published proceedings are listed in code P (above). Unless otherwise noted presentations listed below were at national meetings of the Acoustical Society of America or of the Optical Society of America and an abstract was published. Various invited research presentations at government research centers or universities are not listed.

- M1. S. G. Goosby and P. L. Marston, "Drop Breakup Induced by Modulated Acoustic Radiation Pressure: Photographs," *J. Acoust. Soc. Am.* 68, S30 (1980).
- M2. P. L. Marston and L. Flax, "Glory Contribution to Backscatter from Large Elastic Spheres," *J. Acoust. Soc. Am.* 68, S81 (1980).
- M3. P. L. Marston and D. L. Kingsbury, "Critical Angle Scattering of Light by an Air Bubble: Interference Effects," *J. Opt. Soc. Am.* 70, 1607 (1980).
- M4. P. L. Marston and D. S. Langley, "Glory and Depolarization in Backscattering from Air Bubbles," *J. Opt. Soc. Am.* 70, 1607 (1980).
- M5. P. L. Marston, "Quadrupole Projection of the Radiation Stress: Explanation of the Nonvanishing Long-Wavelength Limit," *J. Acoust. Soc. Am. Suppl.* 69, S70 (1981).
- M6. P. L. Marston, D. S. Langley, and D. L. Kingsbury, "Light Scattering by Bubbles in Liquids: Mie Theory, Physical-Optics Approximation, and Experiments," IUTAM Symposium on the Mechanics and Physics of Bubbles in Liquids, Pasadena, CA, June 1981.
- M7. P. L. Marston and G. L. Pullen, "Cavitation in Water Induced by Reflection of Shock Waves," *Bull. Am. Phys. Soc.* 26, 662 (1981). [American Physical Society, Topical Conference on Shock Waves in Condensed Matter.]
- M8. D. S. Langley and P. L. Marston, "Light Scattering by Bubbles in Liquids," presented at the Northwest Thermal and Fluid Sciences Workshop (Richland, WA, November 1981).
- M9. P. L. Marston, D. S. Langley, and D. L. Kingsbury, "Light Scattering by Bubbles in Liquids," *Bulletin of the American Physical Society* 26, 1259 (1981). [American Physical Society, Division of Fluid Dynamics.]
- M10. S. G. Goosby and P. L. Marston, "Drop Oscillation and Breakup Induced by Modulated Acoustic Radiation Pressure: Photographs," *Bulletin of the American Physical Society* 26, 1265 (1981). [American Physical Society, Division of Fluid Dynamics.]

- M11. P. L. Marston and D. L. Kingsbury, "Comparison of the Partial-Wave Series and a Model for Ultrasonic Scattering from Fluid Spheres Near the Critical Angle," J. Acoust. Soc. Am. Suppl. 70, S6 (1981).
- M12. G. L. Pullen and P. L. Marston, "Dynamic Tension in Water Induced by the Reflection of Shock Waves," J. Acoust. Soc. Am. Suppl. 70, S89 (1981).
- M13. P. L. Marston and D. S. Langley, "Bubbles in Liquid ^4He and ^3He : Mie and Physical-Optics Models of Light Scattering, and Quantum Tunneling and Spinodal Models of Nucleation," presented at the conference "Near Zero: New Frontiers in Physics," Stanford University, Stanford, CA, 1982.
- M14. P. L. Marston and D. S. Langley, "Strong Backscattering and Cross Polarization from Bubbles and Glass Spheres in Water: Models," J. Opt. Soc. Am. 72, 1826 (1982).
- M15. D. S. Langley and P. L. Marston, "Critical-Angle Scattering by a Bubble in Water: Experimental Results," J. Opt. Soc. Am. 72, 1826 (1982).
- M16. B. T. Unger and P. L. Marston, "Rapid Cavitation in Water Induced by the Reflection of Shock Waves," J. Acoust. Soc. Am. Suppl. 72, 40 (1982).
- M17. P. L. Marston and D. S. Langley, "Focusing and Diffraction of Backscattering from Fluid Spheres: Comparison of the Partial-Wave Sum with a Model," J. Acoust. Soc. Am. Suppl. 72, 106 (1982).
- M18. P. L. Marston, T. J. B. Hanson, and K. L. Williams, "Observation of the Acoustic Glory: Scattering from an Elastic Sphere in Near Backward Directions," J. Acoust. Soc. Am. Suppl. 72, 106 (1982).
- M19. P. L. Marston, "Half-order Derivative of a Sine-Wave Burst: Applications to Scattering, Two-Dimensional Radiation, and Photoacoustics," J. Acoust. Soc. Am. Suppl. 73, 99 (1983).
- M20. P. L. Marston, "Light Scattering from Bubbles in Water and Other Liquids," presented at the ONR-NAS Workshop on Propagation Phenomena in Bubbly Media (Rosslyn, VA, May 1983).

- M21. K. L. Williams and P. L. Marston, "Mixed-Mode Acoustic Glory: Model and Experimental Verification," J. Acoust. Soc. Am. Suppl. 74, 109 (1983).
- M22. P. L. Marston and J. H. Crichton, "Radiation Torque on a Sphere Illuminated with Circularly Polarized Light," presented at the 13th International Quantum Electronics Conference (Anaheim, June 1984).
- M23. K. L. Williams and P. L. Marston, "Axially-Focused (Glory) Scattering Due to Surface Waves on Tungsten Carbide Spheres," J. Acoust. Soc. Am. Suppl. 76, 8 (1984).
- M24. P. L. Marston and D. S. Langley, "Optical Scattering Properties of Bubbles of Interest in Acoustics and Cavitation Research," J. Acoust. Soc. Am. Suppl. 76, 30 (1984).
- M25. P. L. Marston and E. H. Trinh, "Light Scattering from Acoustically Levitated Spheroidal Drops: Discovery of a New Hyperbolic Umbilic Diffraction Catastrophe," J. Acoust. Soc. Am. Suppl. 76, 63 (1984).
- M26. P. L. Marston, "Hyperbolic umbilic diffraction catastrophe in the scattering from a penetrable spheroid at short wavelengths," J. Acoust. Soc. Am. Suppl. 77, 78-79 (1985).
- M27. K. L. Williams and P. L. Marston, "Rayleigh-mode backscattering from an elastic sphere: Sommerfeld-Watson transformation and experimental confirmation," J. Acoust. Soc. Am. Suppl. 77, 79 (1985).
- M28. B. T. Unger and P. L. Marston, "Optically stimulated sound from gas bubbles in water: A novel optoacoustic mechanism," J. Acoust. Soc. Am. Suppl. 77, 104 (1985).
- M29. P. L. Marston and B. T. Unger, "Rapid cavitation induced by the reflection of shock waves," Bull. Am. Phys. Soc. 30, 1304 (1985) [APS Topical Conference on Shock Waves Condensed Matter].
- M30. *Invited paper:* P. L. Marston and K. L. Williams, "Rayleigh waves on an elastic sphere: Theory and experiment," presented at the 22nd Annual Meeting of the Society of Engineering Science (Penn. State Univ., 1985).

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- M32. B. T. Unger and P. L. Marston, "Optically stimulated sound from gas bubbles in water: radiation pressure and resonance response," J. Opt. Soc. Am. A 2 (13), P6 (1985).
- M33. E. H. Trinh and P. L. Marston, "Scattering from acoustically levitated spheroidal drops: novel diffraction catastrophes," J. Opt. Soc. Am. A 2 (13), P60 (1985).
- M34. P. L. Marston, "Diffraction catastrophes and inverse scattering: the cusped rainbow of a spheroidal drop," J. Opt. Soc. Am. A 2 (13), P60 (1985).
- M35. D. S. Langley and P. L. Marston, "Forward optical glory of bubbles in liquids: theory and observations," J. Opt. Soc. Am. A 2 (13), P60 (1985).
- M36. P. L. Marston, "Shape of the wavefront which produces a transverse cusp diffraction catastrophe," J. Acoust. Soc. Am. Suppl. 79, 28 (1986).
- M37. K. L. Williams and P. L. Marston, "Synthesis of backscattering from an elastic sphere using the Sommerfeld-Watson Transformation and giving a Fabry-Perot analysis of resonances," J. Acoust. Soc. Am. Suppl. 79, 78 (1986).
- M38. P. L. Marston, "Transverse cusp diffraction catastrophes: Pertinent wavefronts and a Pearcey approximation to the wave field," J. Opt. Soc. Am. A 3 (13), 100 (1986).
- M39. S. C. Billette and P. L. Marston, "Scattering of light by a coalesced bubble in water near the critical scattering angle," J. Opt. Soc. Am. A 3 (13), 117 (1986).
- M40. W. P. Arnott and P. L. Marston, "Backscattering from a slightly spheroidal air bubble in water: A novel unfolding of the optical glory," J. Opt. Soc. Am. A 3 (13), 117 (1986).
- M41. P. L. Marston, "Hyperbolic-umbilic diffraction catastrophes and the tracing of local principal curvatures of wavefronts," J. Acoust. Soc. Am. Suppl. 80, 73 (1986).

- M42. W. P. Arnott and P. L. Marston, "Backscattering of light from spherical and slightly spheroidal air bubbles in water: A novel unfolding of the glory," J. Acoust. Soc. Am. Suppl. 80, 73 (1986).
- M43. P. L. Marston and S. C. Billette, "Scattering of light by a coated bubble in water near the critical and Brewster scattering angles," J. Acoust. Soc. Am. Suppl. 80, 59 (1986).
- M44. P. L. Marston, "Coupling coefficient G for the Fabry-Perot representation of backscattering from spheres and cylinders: Quantitative GTD for elastic objects in water," J. Acoust. Soc. Am. Suppl. 81, 14 (1987).
- M45. P. L. Marston, "Hyperbolic-umbilic focal sections: The wavefield and the merging of rays at caustic lines," J. Acoust. Soc. Am. Suppl. 81, 14 (1987).
- M46. S. G. Kargl and P. L. Marston, "Focused backscattering from hollow spherical shells in water: Lamb waves and the acoustical glory," J. Acoust. Soc. Am. Suppl. 81, 14 (1987).
- M47. P. L. Marston, "Focal-point shifts for the reversed wave in acoustical phase conjugation experiments: Paraxial analysis and analogy with optical holograph," J. Acoust. Soc. Am. Suppl. 82, 12 (1987).
- M48. P. L. Marston, "Coupling of sound with surface waves on fluid-loaded elastic objects described by a generalization of GTD," J. Acoust. Soc. Am. Suppl. 82, 89 (1987).
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- M50. P. L. Marston, "Weak foci in three-dimensional acoustic shocks and shock stability," Bull. Am. Phys. Soc. 32, 2107 (1987); [APS Division of Fluid Dynamics, 1987].
- M51. W. Arnott and P. Marston, "Backscattering of laser light from freely rising spherical and spheroidal bubbles in water," Bull. Am. Phys. Soc. 32, 2104 (1987); [APS Division of Fluid Dynamics, 1987].

- M52. P. L. Marston and B. T. Unger, "Optical levitation of bubbles in water by the radiation pressure of a laser beam," presented at the APS Division of Fluid Dynamics 1987.
- M53. P. L. Marston and C. K. Frederickson, "Transverse cusp and hyperbolic umbilic caustics produced by reflection and transmission: optical experiments and caustic surfaces," presented at Wave Propagation and Scattering in Varied Media (SPIE Conference 927, Orlando, FL, 1988).
- M54. P. L. Marston, "Weak foci in three-dimensional linear shock waves and the stability of real shock waves," J. Acoust. Soc. Am. Suppl. 83, 5 (1988).
- M55. P. L. Marston and K. L. Williams, "GTD for backscattering from elastic objects in water: Phase of the coupling coefficient and a simplified synthesis of the form function," J. Acoust. Soc. Am. Suppl. 83, 94 (1988).
- M56. W. P. Arnott and P. L. Marston, "Harmonic angular perturbation of a toroidal wavefront: A simple unfolding of an axial caustic," J. Acoust. Soc. Am. Suppl. 83, 59 (1988).
- M57. C. E. Dean, W. P. Arnott, and P. L. Marston, "Principal curvatures of general wavefronts and of reflecting or refracting surfaces," J. Acoust. Soc. Am. Suppl. 83, 59 (1988).
- M58. S. M. Bäumer and P. L. Marston, "Brewster angle light scattering from bubbles in water: Observations and potential applications to the acoustics of natural microbubbles," J. Acoust. Soc. Am. Suppl. 83, 108-109 (1988).
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- M60. *Invited Paper*: P. L. Marston (with contributions from W. P. Arnott, S. M. Bäumer, C. E. Dean, and B. T. Unger), "Optics of Bubbles in Water: Scattering Properties, Coatings, and Laser Radiation Pressure," Third International Colloquium of Drops and Bubbles (Monterey, September 1988).

- M61. *Invited Paper:* P. L. Marston, C. E. Dean, and H. J. Simpson, "Light Scattering from Spheroidal Drops: Exploring Optical Catastrophes and Generalized Rainbows," Third International Colloquium of Drops and Bubbles (Monterey, September 1988).
- M62. P. L. Marston, "Product expansion of the S function for scattering from elastic spheres having multiple resonances," *J. Acoust. Soc. Am. Suppl.* **84**, S185 (1988).
- M63. S. G. Kargl and P. L. Marston, "Forward-glory scattering from a spherical shell and backscattering from a convex hemispherical shell," *J. Acoust. Soc. Am. Suppl.* **84**, S208 (1988).
- M64. *Invited Paper:* P. L. Marston, "Elastic resonance amplitudes described by generalized GTD and product expansions of the S function," Symposium on Acoustic Resonance Scattering (Catholic University, Washington, D.C., May 1989).
- M65. S. G. Kargl and P. L. Marston, "Total scattering cross section of an elastic spherical shell: Comparison of exact computations with a GTD model that includes Lamb wave resonances," *J. Acoust. Soc. Am. Suppl.* **85**, 95 (1989).
- M66. S. G. Kargl and P. L. Marston, "GTD synthesis of resonance amplitudes in the backscattering from an elastic spherical shell," *J. Acoust. Soc. Am. Suppl.* **85**, 150 (1989).
- M67. C. K. Frederickson and P. L. Marston, "Transverse Pearcey patterns observed in the reflection of ultrasound from curved surfaces," *J. Acoust. Soc. Am. Suppl.* **85**, 150 (1989).
- M68. J. F. Filler, P. L. Marston, and W. C. Mih, "Local response of the wake of a circular cylinder forced torsional oscillations," *Bull. Am. Phys. Soc.* **34**, 2317-18 (1989); [APS Division of Fluid Dynamics, 1989].
- M69. P. L. Marston, "Contributions to the form function for elastic spheres based on a product expansion of the S function: Numerical tests," *J. Acoust. Soc. Am. Suppl.* **86**, 4 (1989).
- M70. H. J. Simpson and P. L. Marston, "Lips caustics in light backscattered from an acoustically levitated spheroidal water drop," *J. Acoust. Soc. Am. Suppl.* **86**, 5 (1989).

- M71. S. G. Kargl and P. L. Marston, "Quasiperiod of variations in the backscattering and total cross sections of spherical shells," J. Acoust. Soc. Am. Suppl. 86, 5 (1989).
- M72. S. G. Kargl and P. L. Marston, "Longitudinal axial resonances in the form function for backscattering from a fluid shell," J. Acoust. Soc. Am. Suppl. 87, 35 (1990).
- M73. S. G. Kargl and P. L. Marston, "Ray synthesis of the form function for backscattering from hollow elastic shells including leaky lamb waves and longitudinal resonances," J. Acoust. Soc. Am. Suppl. 87 35 (1990).
- M74. C. E. Dean and P. L. Marston, "Critical angle scattering: An asymptotic series approximations, J. Acoust. Soc. Am. Suppl. 87, 35 (1990).
- M75. J. R. Filler and P. L. Marston, "Response of the shear layers separating from a circular cylinder to small amplitude rotational oscillations," J. Acoust. Soc. Am. 87, 150 (1990).
- M76. H. J. Simpson, S. G. Kargl, and P. L. Marston, "Mixing of sound in water near a free surface," 12th International Symposium on Nonlinear Acoustics (Austin, 1990).
- M77. S. G. Kargl and P. L. Marston, "Anomalies in the ray synthesis of backscattering from hollow elastic spherical shells," J. Acoust. Soc. Am. Suppl. 88, 15 (1990).
- M78. C. F. Frederickson and P. L. Marston, "Observations of transverse cusp diffraction catastrophes produced by reflecting long and short ultrasonic bursts from a curved metal surface in water," J. Acoust. Soc. Am. Suppl. 88, 16 (1990).
- M79. P. L. Marston and H. J. Simpson, "Surface grating contribution to the mixing of reflected ultrasonic beams: Approximate analysis," J. Acoust. Soc. Am. Suppl. 88, 76 (1990).
- M80. *Invited Paper*: P. L. Marston and C. K. Frederickson, "Aberrated foci in the time and frequency domains and experiments with acoustical diffraction catastrophes," J. Acoust. Soc. Am. 90, 2288 (1991); presented at the 122nd meeting of the Acoustical Society of America (Houston, November 1991).

- M81. C. K. Frederickson and P. L. Marston, "Imaged travel time surface of the transverse cusp caustic produced by reflection from a curved surface and the shape of reflected transients," J. Acoust. Soc. Am. **91**, 2470 (1992); presented at the 123rd meeting of the Acoustical Society of America (Salt Lake City, May 1992).

IV. RAY METHODS FOR THE SCATTERING OF SOUND BY ELASTIC OBJECTS IN WATER

A. Glory Scattering and Transmitted Wave Contributions to Scattering by Fluid and Solid Spheres.

(a) Selected Publications.

1. P. L. Marston and D. L. Kingsbury, "Acoustic Scattering from Fluid Spheres: Diffraction and Interference Near the Critical Scattering Angle," Journal of the Acoustical Society of America **70**, 1488-1495 (1981).
2. P. L. Marston and D. S. Langley, "Glory- and Rainbow-Enhanced Acoustic Backscattering from Fluid Spheres: Models for Diffracted Axial Focusing," Journal of the Acoustical Society of America **73**, 1464-1475 (1983).
3. P. L. Marston, K. L. Williams, and T. J. B. Hanson, "Observation of the Acoustic Glory: High-Frequency Backscattering from an Elastic Sphere," Journal of the Acoustical Society of America **74**, 605-618 (1983).
4. K. L. Williams and P. L. Marston, "Mixed-Mode Acoustical Glory Scattering from a Large Elastic Sphere: Model and Experimental Verification," Journal of the Acoustical Society of America **76**, 1555-1563 (1984).
5. P. L. Marston, "Half-Order Derivative of Sine-Wave Burst: Applications to Two-Dimensional Radiation, Photoacoustics, and Focused Scattering from Spheres and a Torus," Journal of the Acoustical Society of America **76**, 291-295 (1984).
6. W. P. Arnott and P. L. Marston, "Unfolding axial caustics of glory scattering with harmonic angular perturbations of toroidal wavefronts," Journal of the Acoustical Society of America **85**, 1427-40 (1989).

7. P. L. Marston, "Geometrical and Catastrophe Optics Methods in Scattering," in High Frequency and Pulse Scattering, in Physical Acoustics, Vol. XXI, edited by R. N. Thurston and A. D. Pierce (Academic Press, Boston, 1992) pp. 1-234.

(b) Theses, Dissertations, or Reports: S2, S3, S4, I3, and I4.

Comments: Publication 7 gives a physical optics theory of acoustical focused spherical reflectors.

B. Ray Methods for Rayleigh and Whispering Gallery Wave Contributions to Scattering by Solid Spheres or Cylinders.

(a) Selected Publications.

1. K. L. Williams and P. L. Marston, "Axially Focused (Glory) Scattering due to Surface Waves Generated on Spheres: Model and Experimental Confirmation using Tungsten Carbide Spheres," *Journal of the Acoustical Society of America* **78**, 722-728 (1985).

2. K. L. Williams and P. L. Marston, "Backscattering from an elastic sphere: Sommerfeld-Watson transformation and experimental confirmation," *Journal of the Acoustical Society of America* **78**, 1093-1102 (1985); **79**, 2091 (1986).

3. K. L. Williams and P. L. Marston, "Synthesis of backscattering from an elastic sphere using the Sommerfeld-Watson transformation and giving a Fabry-Perot analysis of resonances," *Journal of the Acoustical Society of America* **79**, 1702-1708 (1986).

4. K. L. Williams and P. L. Marston, "Scattering from an aluminum sphere: Fabry-Perot analysis of resonances based on the Watson transformation," in Proceedings of the 12th International Congress on Acoustics (Beauregard Press, Toronto Canada, 1986), pp. 11-2.1/2.2.

5. P. L. Marston, "GTD for backscattering from elastic spheres and cylinders in water, and the coupling of surface elastic waves with the acoustic field," *Journal of the Acoustical Society of America* **83**, 25-37 (1988).

6. P. L. Marston, "Geometrical and Catastrophe Optics Methods in Scattering," in High Frequency and Pulse Scattering, in *Physical Acoustics*, Vol. XXI, edited by R. N. Thurston and A. D. Pierce (Academic Press, Boston, 1992) pp. 1-234.

(b) Theses, Dissertations, or Reports: T4, S4, S5, S6, and S7.

C. Ray Methods for Scattering by Shells with Application to Spheres, Cylinders, or Hemispheres.

(a) Selected Publications.

1. P. L. Marston, "GTD for backscattering from elastic spheres and cylinders in water, and the coupling of surface elastic waves with the acoustic field," *Journal of the Acoustical Society of America* **83**, 25-37 (1988).

2. P. L. Marston and S. G. Kargl, "Backscattering of sound from an empty spherical shell in water," in Shock Wave Compression of Condensed Matter [Proceedings of a Symposium in Honor of George E. Duvall, Pullman, WA, Sept. 1988], edited by Y. M. Gupta (Shock Dynamics Lab., Washington State University, Pullman, 1988) pp. 58-64.

3. P. L. Marston, "Phase velocity of Lamb waves on a spherical shell: Approximate dependence on curvature from kinematics," *Journal of the Acoustical Society of America* **85**, 2663-65 (1989).

4. P. L. Marston and S. G. Kargl, "Elastic surface wave contributions to backscattering from smooth elastic objects described by a generalization of GTD," in Oceans' 89 (IEEE Publication No. 89CH2780-5, New York, 1989) pp. 1194-1198.

5. S. G. Kargl and P. L. Marston, "Ray synthesis of Lamb wave contributions to the total scattering cross section for an elastic spherical shell," *Journal of the Acoustical Society of America* **80**, 1103-1113 (1990).

6. S. G. Kargl and P. L. Marston, "Longitudinal resonances of the form function for backscattering from a spherical shell: Fluid shell case," *Journal of the Acoustical Society of America* **88**, 1114-1112 (1990).
 7. P. L. Marston, S. G. Kargl, and K. L. Williams, "Rayleigh, Lamb, and Whispering Gallery Wave Contributions to Backscattering from Smooth Elastic Objects in Water Described by a Generalization of GTD," in Elastic Waves and Ultrasonic Nondestructive Evaluation (IUTAM Symposium), edited by S. K. Datta, J. D. Achenbach, and Y. S. Rajapakse (Elsevier Science Publishers, Amsterdam, 1990) pp. 211-216.
 8. P. L. Marston and S. G. Kargl, "Scattering from hollow shells: Quantitative ray representations of amplitudes," in Proceedings of the International Congress on Recent Developments in Air and Structure Borne Sound and Vibration, edited by M. J. Crocker (Auburn University, 1990) pp. 565-69.
 9. S. G. Kargl and P. L. Marston, "Ray synthesis of the form function for backscattering from an elastic spherical shell: Leaky Lamb waves and longitudinal resonances," *Journal of the Acoustical Society of America* **89**, 2545-2558 (1991).
 10. P. L. Marston, S. G. Kargl, and N. H. Sun, "Elastic resonance amplitudes described by generalized GTD and by product expansions of the S-matrix," in Acoustic Resonance Scattering edited by H. Uberall (Gordon and Breach, New York, 1992) pp. 305-333.
 11. P. L. Marston, "Geometrical and Catastrophe Optics Methods in Scattering," in High Frequency and Pulse Scattering, in *Physical Acoustics*, Vol. XXI, edited by R. N. Thurston and A. D. Pierce (Academic Press, Boston, 1992) pp. 1-234.
- (b) Theses, Dissertations, or Reports: T11, I7, S6, S7,S8, S9.
- (c) Selected Presentations.

1. S. G. Kargl and P. L. Marston, "Focused backscattering from hollow spherical shells in water: Lamb waves and the acoustical glory," J. Acoust. Soc. Am. Suppl. 81, 14 (1987).
2. P. L. Marston, "Coupling coefficient G for the Fabry-Perot representation of backscattering from spheres and cylinders: Quantitative GTD for elastic objects in water," J. Acoust. Soc. Am. Suppl. 81, 14 (1987).
3. P. L. Marston, "Coupling of sound with surface waves on fluid-loaded elastic objects described by a generalization of GTD," J. Acoust. Soc. Am. Suppl. 82, 89 (1987).
4. P. L. Marston and K. L. Williams, "GTD for backscattering from elastic objects in water: Phase of the coupling coefficient and a simplified synthesis of the form function," J. Acoust. Soc. Am. Suppl. 83, 94 (1988).
5. S. G. Kargl and P. L. Marston, "Forward-glory scattering from a spherical shell and backscattering from a convex hemispherical shell," J. Acoust. Soc. Am. Suppl. 84, S208 (1988).

Comments: Subsequently quantitative ray methods for scattering by shells were also developed by several other groups. See e.g. References 1-3. The ray description of the effects of curvature on reflection by a spherical "fluid" shell given in publication 6 (with application to solid shells in publication 9) was extended to the case of cylindrical shells in publications 10 and 11.

D. Product Expansions of the S Function for Scattering by Elastic Objects.

(a) Selected Publications.

1. P. L. Marston, S. G. Kargl, and N. H. Sun, "Elastic resonance amplitudes described by generalized GTD and by product expansions of the S-matrix," in Acoustic Resonance Scattering edited by H. Uberall (Gordon and Breach, New York, 1992) pp. 305-333.

(b) Theses, Dissertations, or Reports: S8, S9.

(c) Selected Presentations.

1. P. L. Marston, "Product expansion of the S function for scattering from elastic spheres having multiple resonances," *J. Acoust. Soc. Am. Suppl.* **84**, S185 (1988).
2. P. L. Marston, "Contributions to the form function for elastic spheres based on a product expansion of the S function: Numerical tests," *J. Acoust. Soc. Am. Suppl.* **86**, 4 (1989).

Comments: Product expansions were subsequently applied to shells by Sammelman and Hackman (Reference 4).

V. ACOUSTICAL AND OPTICAL DIFFRACTION CATASTROPHES

(a) Selected Publications.

1. P. L. Marston and E. H. Trinh, "Hyperbolic umbilic diffraction catastrophe and rainbow scattering from spheroidal drops," *Nature (London)* **312**, 529-531 (1984).
2. P. L. Marston, "Cusp diffraction catastrophe from spheroids: generalized rainbows and inverse scattering," *Optics Letters* **10**, 588-590 (1985).
3. P. L. Marston, "Transverse cusp diffraction catastrophes: Some pertinent wavefronts and a Pearcey approximation to the wavefield," *Journal of the Acoustical Society of America* **81**, 226-232 (1987).
4. P. L. Marston, "Wavefront geometries giving transverse cusp and hyperbolic umbilic foci in acoustic shocks," in *Shock Waves in Condensed Matter 1987*, edited by S. C. Schmidt and N. C. Holmes (Elsevier Science Publishers, Amsterdam, 1988) pp. 203-206.
5. P. L. Marston, "Surface shapes giving transverse cusp catastrophes in acoustic or seismic echoes," in *Acoustical Imaging Vol. 16*, edited by L. W. Kessler (Plenum, New York, 1988) pp. 579-588.

6. W. P. Arnott and P. L. Marston, "Unfolding axial caustics of glory scattering with harmonic angular perturbations of toroidal wavefronts," *Journal of the Acoustical Society of America* **85**, 1427-40 (1989).
 7. P. L. Marston and C. K. Frederickson, "Wavefields of Linear Cusp Caustics Germane to Nonlinear Foci," in Frontiers of Nonlinear Acoustics: 12th ISNA, edited by M. F. Hamilton and D. T. Blackstock (Elsevier, London, 1990), pp. 203-208.
 8. C. E. Dean and P. L. Marston, "Opening rate of the transverse cusp diffraction catastrophe in light scattered from oblate spheroidal drops," *Applied Optics* **30**, 3443-3451 (1991).
 9. W. P. Arnott and P. L. Marston, "Unfolded optical glory of spheroids: Backscattering of laser light from freely rising spheroidal air bubbles in water," *Applied Optics* **30**, 3429-3442 (1991).
 10. H. J. Simpson and P. L. Marston, "Scattering of white light from levitated oblate water drops near rainbows and other diffraction catastrophes," *Applied Optics* **30**, 3468-3473 + 3547 [Color Plates 13-16] (1991).
 11. C. K. Frederickson and P. L. Marston, "Transverse cusp diffraction catastrophes preceded by the reflection of ultrasonic tone bursts from a curved surface in water: Observations," *J. Acoust. Soc. Am.* **92**, 2869-2877 (1992).
 12. P. L. Marston, "Geometrical and Catastrophe Optics Methods in Scattering," in High Frequency and Pulse Scattering, in *Physical Acoustics*, Vol. XXI, edited by R. N. Thurston and A. D. Pierce (Academic Press, Boston, 1992) pp. 1-234.
- (b) Theses, Dissertations, or Reports: T8, T9, T12, I6, I8, I9, I12, S4, S5, S6, S7, S8, and S9.

Comments: Our experimental and local analytical results for the more complicated of the diffraction catastrophes studied motivated Nye (Ref. 5) to analyze the global organization of the diffraction catastrophes relevant not just to our experimental situations.

VI. LIGHT SCATTERING BY BUBBLES IN WATER OR OTHER DIELECTRICS

A. General Overviews: Selected Publications.

1. P. L. Marston, D. S. Langley, and D. L. Kingsbury, "Light Scattering by Bubbles in Liquids: Mie Theory, Physical-Optics Approximations, and Experiments, Applied Scientific Research 38, 373-384 (1982).
2. P. L. Marston, W. P. Arnott, S. M. Bäumer, C. E. Dean, and B. T. Unger, "Optics of Bubbles in Water: Scattering Properties, Coatings, and Laser Radiation Pressure," in Drops and Bubbles. Third International Colloquium edited by T. G. Wang (AIP Conference Proceedings 197, New York, 1989) pp. 461-480.
3. P. L. Marston, "Light scattering from bubbles in water," in Oceans' 89 (IEEE Publication No. 89CH2780-5, New York, 1989) pp. 1186-1193.
4. *Invited Paper*: P. L. Marston, T. J. Asaki, J. S. Stroud, and E. H. Trinh, "Oscillations of bubbles driven by modulated ultrasonic radiation pressure their optical detection, and the optical detection of transient bubble oscillations associated with rain noise," in *Proceedings of the 14th International Congress on Acoustics*, edited by Li Peizi (Beijing, 1992), pp. C-2-5.1, 2.
5. P. L. Marston, "Geometrical and Catastrophe Optics Methods in Scattering," in High Frequency and Pulse Scattering, in Physical Acoustics, Vol. XXI, edited by R. N. Thurston and A. D. Pierce (Academic Press, Boston, 1992) pp. 1-234.

B. Near Critical-Angle Scattering: Selected Publications.

1. P. L. Marston and D. L. Kingsbury, "Scattering by a Bubble in Water Near the Critical Angle: Interference Effects," J. Opt. Soc. Am. 71, 192-196 (1981).
2. D. L. Kingsbury and P. L. Marston, "Mie Scattering Near the Critical Angle of Bubbles in Water," J. Opt. Soc. Am. 71, 358-361 (1981).

3. D. L. Kingsbury and P. L. Marston, "Scattering by Bubbles in Glass: Mie Theory and Physical Optics Approximation," *Applied Optics* **20**, 2348-2350 (1981).
4. P. L. Marston, J. L. Johnson, S. P. Love, and B. L. Brim, "Critical Angle Scattering of White Light from a Cylindrical Bubble in Glass: Photographs of Colors and Computations," *Journal of the Optical Society of America* **73**, 1658-1664 + Plate X (1983).
5. D. S. Langley and P. L. Marston, "Critical-Angle Scattering of Laser Light from Bubbles in Water: Measurements, Models, and Applications to Sizing of Bubbles," *Applied Optics* **23**, 1044-1054 (1984).
6. P. L. Marston, S. C. Billette, and C. E. Dean, "Scattering of light by a coated bubble in water near the critical and Brewster scattering angles," in *Ocean Optics IX*, M. A. Blizard, ed., *Proc. SPIE* **925**, 308-316 (1988).
7. P. L. Marston, "Colors observed when sunlight is scattered by bubble clouds in sea water," *Applied Optics* **30**, 3479-3484 + 3549 [Color Plate 20] (1991).
8. C. E. Dean and P. L. Marston, "Critical angle light scattering from bubbles: an asymptotic series approximation," *Applied Optics* **30**, 4764-4776 (1991).

C. Glory Scattering: Selected Publications.

1. D. S. Langley and P. L. Marston, "Glory in the Optical Backscattering from Air Bubbles," *Physical Review Letters* **47**, 913-916 (1981).
2. P. L. Marston and D. S. Langley, "Glory in Backscattering: Mie and Model Predictions for Bubbles and Conditions on Refractive Index in Drops," *Journal of the Optical Society of America* **72**, 456-459 (1982).
3. P. L. Marston, "Uniform Mie-theoretic Analysis of Polarized and Cross-Polarized Optical Glories," *Journal of the Optical Society of America* **73**, 1816-1818 (1983).
4. P. L. Marston and D. S. Langley, "Strong Backscattering and Cross-Polarization from Bubbles and Glass Spheres in Water," *Ocean Optics VII Proceedings of the Society of Photo-Optical Instrumentation Engineers* **489**, 130-141 (1984).

5. W. P. Arnott and P. L. Marston, "Optical glory of small freely-rising gas bubbles in water: Observed and computed cross-polarized backscattering patterns," *Journal of the Optical Society of America A* **5**, 496-506 (1988).
6. W. P. Arnott and P. L. Marston, "Unfolded optical glory of spheroids: Backscattering of laser light from freely rising spheroidal air bubbles in water," *Applied Optics* **30**, 3429-3442 (1991).
7. D. S. Langley and M. J. Morrell, "Rainbow-enhanced forward and backward glory scattering," *Applied Optics* **30**, 3459-3467 (1991).
8. D. S. Langley and P. L. Marston, "Forward glory scattering from bubbles," *Applied Optics* **30**, 3452-3458 (1991).

D. Optical Levitation of Bubbles and Photoacoustic Response of Bubbles or Drops: Selected Publications.

1. B. T. Unger and P. L. Marston, "Optical levitation of bubbles in water by the radiation pressure of a laser beam: an acoustically quiet levitator," *Journal of the Acoustical Society of America* **83**, 970-975 (1988).
2. B. T. Unger and P. L. Marston, "Optically stimulated sound from oil drops and gas bubbles in water: thermal and radiation pressure optoacoustic mechanisms," in *Ocean Optics IX*, M. A. Blizard, ed., *Proc. SPIE* **925**, 326-333 (1988).

E. Theses or Dissertations.

1. D. L. Kingsbury, "Light Scattering Near the Critical Angle of Air Bubbles in Water and Glass," M.S. Thesis, 1980.
2. D. S. Langley, "Light Scattering from bubbles in Liquids," Ph.D. dissertation, 1984. DTIC AD-A158736.

3. S. C. Billette, "Computational Analysis of the Effects of Surface Films on the Optical Scattering Properties of Bubbles in Water," M.S. Thesis, 1986. DTIC AD-A173999.
4. B. T. Unger, "Optically Stimulated Sound from Gas Bubbles in Water," Ph.D. dissertation, 1986.
5. S. M. Bäumer, "Observation of Brewster Angle Light Scattering from Air Bubbles Rising in Water," M.S. Thesis, 1988. DTIC AD-A119582.
6. W. P. Arnott, "Generalized Glory Scattering from Spherical and Spheroidal Bubbles in Water: Unfolding Axial Caustics with Harmonic Angular Perturbations of Toroidal Wavefronts," Ph.D. dissertation, 1988.
7. C. E. Dean, "Analysis of scattered light: I. Asymptotic series for critical angle scattering from bubbles; II. The opening rate of the transverse cusp from oblate drops," Ph.D. dissertation, 1989.

F. Reports: I5, I6, I11, S1, S2, S3, S4, S5, S6, S7, S8, and S9.

G. Selected Presentations.

1. P. L. Marston, D. S. Langley, and D. L. Kingsbury, "Light Scattering by Bubbles in Liquids: Mie Theory, Physical-Optics Approximation, and Experiments," IUTAM Symposium on the Mechanics and Physics of Bubbles in Liquids, Pasadena, CA, June 1981.
2. P. L. Marston and D. S. Langley, "Optical Scattering Properties of Bubbles of Interest in Acoustics and Cavitation Research," J. Acoust. Soc. Am. Suppl. 76, 30 (1984).

Comments: Results from our work have impacted the development of light scattering for the diagnostics of bubble dynamics in acoustics (see e.g. Ref. 6) and in fluid mechanics (see e.g. Ref. 7 and 8). The work has also motivated the theoretical exploration of a new class of "weak caustics" (Nussenzveig, Ref. 9). There has been subsequent interest in optical levitation and the photoacoustic response as noted in References 10 and 11.

VII. NONLINEAR ACOUSTICS AND RADIATION PRESSURE

A. Response of Drops or Bubbles to Acoustic Radiation Pressure.

(a) Selected Publications.

1. P. L. Marston, S. E. LoPorto-Arione, and G. L. Pullen, "Quadrupole Projection of the Radiation Pressure on a Compressible Sphere," *J. Acoust. Soc. Am.* **69**, 1499-1501 (1981).
2. P. L. Marston, S. G. Goosby, D. S. Langley, and S. E. LoPorto-Arione, "Resonances, Radiation Pressure, and Optical Scattering Phenomena of Drops and Bubbles," in Proceedings of the Second International Colloquium on Drops and Bubbles, edited by D. H. LeCroisette (Jet Propulsion Laboratory, Publication 82-7, Pasadena, 1982), pp. 166-174.
3. P. L. Marston and S. G. Goosby, "Ultrasonically stimulated low-frequency oscillation and breakup of immiscible liquid drops: Photographs," *Physics of Fluids* **28**, 1233-1242 (1985).

(b) Theses, Dissertations, and Reports: T2 and I1.

Comments: The calculation of the quadrupole and $l = 3$ shape changes of drops or bubbles given in publications 1 and 2 were for the low frequency and weak deformation limits. Subsequently a more analytically based approach made higher frequency calculations possible giving "excellent agreement" with Marston's results in the appropriate limit (Jackson et al. Ref. 12). With support from the ONR Ocean Engineering Division (grant N00014-91-J-1374) the coupling mechanism has been exploited to study the surface oscillation properties of bubbles (Ref. 13 and P32).

B. Rapid Cavitation Resulting from the Reflection of a Shock Pulse.

(a) Selected Publications.

1. P. L. Marston and G. L. Pullen, "Cavitation in Water Induced by the Reflection of Shock Waves," in Shockwaves in Condensed Matter-1981, edited by

W. J. Nellis, L. Seaman, and R. A. Graham (American Institute of Physics, Proceedings No. 78, New York, 1982), pp. 515-519.

2. P. L. Marston and B. T. Unger, "Rapid Cavitation Induced by the Reflection of Shock Waves" in Shock Waves in Condensed Matter, Y. M. Gupta, editor (Plenum Press, NY, 1986) pp. 401-405.

(b) Theses, Dissertations, or Reports: I2, S4, References 14.

Comments: The experiments in publication 2 showed a rapid cavitation signature due to the reflection of an impact generated 1.7 μ s duration compressional pulse off of a quasi-free water-Mylar-air surface. A displacement optical interferometer was used for the diagnostics. Subsequently there was a growth of interest in rapid cavitation processes (see e.g. Ref. 15).

C. Nonlinear Three-Wave Mixing and Acoustical Phase Conjugation.

(a) Publications and Dissertations.

1. P. L. Marston and S. G. Kargl, "Wavefront Reversal and Difference Frequency Generation Via Three-Wave Mixing in a Bubble Layer," in Frontiers of Nonlinear Acoustics: 12th ISNA, edited by M. F. Hamilton and D. T. Blackstock (Elsevier, London, 1990), pp. 514-519.

2. H. J. Simpson, "Interaction of Sound with Sound by Novel Mechanisms: Ultrasonic Four-Wave Mixing Mediated by a Suspension and Ultrasonic Three-Wave Mixing at a Free Surface," Ph.D. dissertation 1992.

(b) Reports: S6, S7, S8, and S9.

Comments: As reviewed in report S8, the initial attempts to use microbubbles stabilized by a Nuclepore membrane as a nonlinear layer appear to have been complicated by the rapid rate for such bubbles to dissolve. Report S9 summarizes unsuccessful experiments with layers of macroscopic bubbles carried in cooperation with the Naval Coastal Systems Center (Panama City, Fl.) in 1989. The general magnitude and focal point locations of generated waves are discussed in publication 1. The part of the H. J. Simpson's Ph.D. dissertation supported by Contract N00014-85-C-0141 concerns the successful observation

of three-wave acoustic interaction at a free water surface which in effect takes the place of the bubble layer analyzed in publication 1. Simpson's focal point locations for the generated wave and general mixing magnitude were in agreement with predictions though due to hydrophone calibration uncertainties in the MHz range, there were significant amplitude uncertainties. A major portion of the instrumentation was adapted to the study of four-wave mixing in suspensions (supported by N00014-89-J-3088) that is reported in Simpson's dissertation and also in Ref. 16. Reports S6 and S8 discuss plausible phase conjugation mechanisms based in the reflection by vibrating surfaces. Subsequent noteworthy developments by others include parametric amplification in a bubble layer (Ref. 17) and an ultrasonic phase conjugation that used a 20-element piezoelectric transducer array (Ref. 18). A method based on a reflector with an artificial nonlinearity has been proposed (Ref. 19).

D. Wave Phenomena in a Ripple Tank.

Comments: In his M.S. degree project report I10 titled "Experiments on Wave Phenomena in a Ripple Tank," J. M. Winey demonstrates the mechanical generation and capacitor bridge detection of weakly dispersive wave packets in a ripple tank. The focusing of packets was also demonstrated. The packets were made weakly dispersive by choosing the depth such that surface tension and gravitational dispersion approximately cancel. The original idea was to demonstrate in two dimensions nonlinear mixing phenomena analogous to ones considered in Section C but that would require more area than Winey's 25cm \times 50cm tank.

E. Response of Hydrodynamic Shear Layers Separating from a Circular Cylinder to Small Amplitude Rotational Oscillations.

(a) Publications and Dissertations.

1. J. R. Filler, "Response of the shear layer separating from a circular cylinder to small amplitude rotational oscillation," Ph.D. dissertation, 1989.
2. J. R. Filler, P. L. Marston, and W. C. Mih, "Response of the shear layers separating from a circular cylinder to small-amplitude rotational oscillations," *Journal of Fluid Mechanics* **231**, 481-499 (1991).

(b) Reports: S9.

Comments: The experiment demonstrated a novel fluid-structure interaction associated with flow past a cylinder. The results are reviewed by Griffin (Ref. 20).

F. Radiation Torque on a Sphere Caused by Circularly Polarized Light.

(a) Publications.

1. P. L. Marston and J. H. Crichton, "Radiation Torque on a Sphere Caused by a Circularly Polarized Electromagnetic Wave," *Physical Review A* **30**, 2508-2516 (1984) reprinted in Selected Papers on Light Scattering, edited by Milton Kerker, Proc. SPIE 951, 414-422 (1988).
2. P. L. Marston and J. H. Crichton, "Radiation Torque on a Sphere Illuminated with Circularly Polarized Light," *Journal of the Optical Society of America B* **1**, 528-529 (1984).
3. P. L. Marston and J. H. Crichton, "Radiation torque on a sphere illuminated with circularly polarized light and the angular momentum of scattered radiation," in Proceedings of the Chemical Research and Development Center's 1984 Scientific Conference on Obscuration and Aerosol Research, edited by R. H. Kohl and D. Stroud (U.S. Army, Aberdeen Proving Ground, MD, 1985) pp. 233-238.

(b) Reports: S4.

Comments: The torque is proportional to the absorption cross section. The analysis was subsequently generalized by other groups (e.g. Refs. 21-23).

VIII. SURVEY OF RAY METHODS IN SCATTERING

Figure 1 shows the table of contents of a tutorial survey partially partially supported by N00014-85-C-0141. The project was completed with support from N00014-89-J-3088 and describes several new results.

Geometrical and Catastrophe Optics Methods in Scattering

PHILIP L. MARSTON

Department of Physics, Washington State University, Pullman, Washington

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Figure 1 -- Table of contents of Publication B3 from *Physical Acoustics* Vol. 21.

IX. REFERENCES

Comments: While it may be too early to access the impact of the sponsored research, it is perhaps noteworthy that with the exception of References 13, 14, and 16-19, the References listed below are examples of work by other groups that cite the sponsored work.

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